Ground settlement due to shield tunneling through gravelly soils in Hsinchu

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ABSTRACT

This paper reports the field monitored surface settlements due to the construction of 161 kV power-cable shield tunnels in Hsinchu. The soils encountered during tunneling were mostly cobble and gravelly soils. Four earth-pressure-balance shield machines with outside diameters 6.24 and 6.70 m were used for tunnel excavation. When driven through gravelly soils, significant cutter head wearing was observed. Base on field observation data, the following conclusions were made. The maximum surface settlement was reached at approximately 30 days after the passage of the face. The maximum surface settlement achieved was only 5 to 6 mm. The field monitored settlement-time data were in fairly good agreement with the curves estimated with the hyperbolic model. The maximum surface settlements induced in cobble and gravelly soils were significantly less than those induced in clayey and sandy soils. This is most probably due to the high stiffness and shear strength of the gravelly soil, which reduced the ground deformation due to subsurface excavation. The induced settlement trough was wider than those induced in stiff clay, soft to hard clay, and sand above ground water table.

Key words: shield tunneling, gravelly soils, maximum settlement, settlement-time relationship, settlement trough

1 INTRODUCTION

In recent years, due to the rapid development of urban areas, a lot of public facilities such as the Mass Rapid Transit (MRT) systems, sewerage systems, and high-voltage power-cable tunnels have been constructed. Because of the disruptive effects of the cut-and-cover method, it has been becoming more popular to employ the shield tunneling method for passing under commercial areas with heavy traffic.

In order to provide customers in Taiwan with safe and reliable power, the Taiwan Power Company has formulated the 7th Transmission and Substation Project. This Project, with a total investment of approximately US$ 8.0 million, has been scheduled from January of 2010 to the end of 2015. Many overhead transmission lines in Taiwan were replaced by underground cables. To avoid the disruption of heavy traffic, the shield machines were used to construct the tunnels for underground power cables.

On the western coast of Taiwan, from Taoyuan, Hsinchu, and Taichung, gravelly soil deposits were often encountered. With the growing construction of MRT, sewerage, and underground power-transmission systems on the west coast, cases of tunneling through gravelly soils are rapidly increasing.

Peck (1969) suggested that the surface settlement trough due to shield tunneling could be approximated by a normal distribution function. In his study, the trough width parameter i was suggested for tunneling in stiff clay, soft clay and sand. No suggesting regarding parameter i for tunneling in gravelly soils was provided. Fujita (1982) summarized the maximum surface settlement for tunneling in clay and sand. Unfortunately, no maximum surface settlement due to shield tunneling in gravelly soils was reported.

In the paper, shield tunneling for the construction of 161 kV power-cable tunnels in Hukou, Hsinchu was introduced. Subjects discussed included the subsurface soil conditions, shield tunneling in gravel, wearing of cutter head, and the monitoring array. Based on the field observation, the settlement-time relationship, and the characteristics of the surface settlement trough were investigated.

2 SHIELD TUNNELING IN HSINCHU

Fig. 1 illustrates the plan of Chu-Kung 161 kV power cable tunnel at Hukou, Hsinchu, Taiwan. The shield tunneling started from the Chu-Kung shaft (near Taiwan Highway 1, 53.5 K), along the Taiwan Highway 1 to the Ben-Ji-Wo shaft, and ended at the Yamazaki shaft. The total length of tunneling was 8,390 m, with 9 shafts and 8 sections of shield tunnel. Four earth-pressure-balance (EPB) shield machines were used for construction; each shield drove 2 sections of tunnel. From Chu-Kung shaft to Ben-Ji-Wo shaft, the shield outside diameter was 6.70 m and the inner diameter was 6.20 m. From Ben-Ji-Wo shaft to Yamazaki shaft, the shield outside diameter was 6.24 m and the inner diameter was 5.60 m. The owner of this project is Taiwan Power Company, and the contractor is a Joint Venture of Chieh-Hsing Construction Company and Shimizu Corporation.

2.1 Subsoil conditions

The geological profile of the Chu-Kung power cable tunnel and shafts was indicated in Fig. 2. A series of 13 bore holes were driven down to 35 m below ground surface. Ground water table varied from 2.0 to 6.3 m below ground surface. In descending order, properties of the three sub-layers were as follows:

(1) Surface fill (SF): medium dense sand, located at 0 to 3.0 m below ground surface.

(2) Silty gravel: sandy silt and clay with gravel, 3 to 7 m thick, SPT N-value of 10.

(3) Gobble and gravelly soil: cobble and gravel with sand, silt and clay, thickness up to 30 m, SPT N-value greater than 50.

It can be observed in Fig. 2 that, for this project the shield tunneling was carried out mostly in the cobble and gravelly soils.

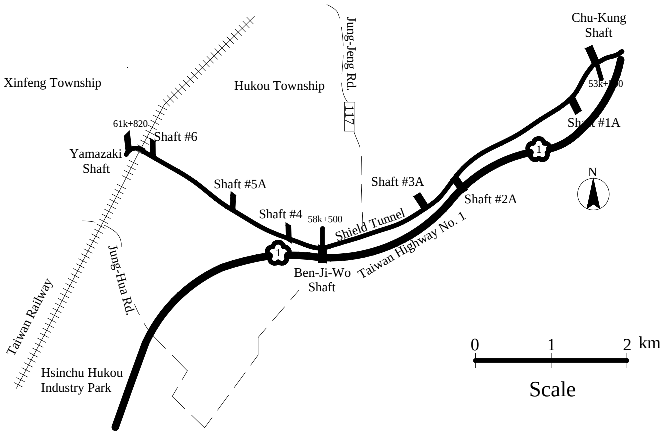

Fig. 1. Plan of Chu-Kung 161 kV power cable tunnel.

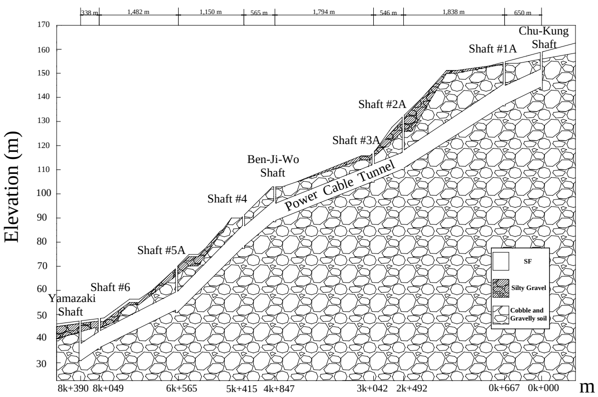

Fig. 2. Geological profile of Chu-Kung 161 kV power cable tunnel.

(a) 45 degree-view

(b) Top-view

Fig. 3. Articulate EPB shield machine before tunneling.

Fig. 4. Ribbon-type screw conveyor to transport cobble particles.

2.2 Shield tunneling in gravelly soils

Fig. 3 (a) and (b) showed the articulate mud-injection EPB shield machine used for this project, which was manufactured by the Kawasaki Heavy Industries Ltd. in Japan. For the convenience of water drainage, Fig. 2 showed the tunnels sections were driven from lower elevations on the west, toward higher elevations on the east. Precast reinforced-concrete lining segments used were 0.25 m-thick and 1.2 m-long. For the curved parts (minimum R = 150 m) of the tunnel, the lining segments were only 0.75 m-long. Fig. 4 showed the ribbon-type screw conveyor was used. Without the central axis, large cobble particle could pass through the conveyor more easily.

Both mud and foam were injected into the cobble and gravelly soil in front of the cutter disc. The mud and foam adsorbed around the soil particles could help to reduce the friction among the particles, and to reduce the permeability of the gravelly soil.

2.3 Wearing of cutter bits

To drive through the cobble and gravelly soils with large and hard particles, Fig. 3 (a) showed, many roller bits and cutter bits made of extra-hard alloy were arranged on the cutter disc. After tunneling from the Yamazaki shaft to shaft No. 6, Fig. 5 indicated the roller bits and cutter bits were more seriously worn than expected. Before tunneling for the second section, all roller and cutter bits on the cutter disc were replaced with new ones. During excavation for its second section, the thrust and torque applied on the cutter disc were closely monitored. The wearing of the cutting bits was inspected from the man-hole on the cutter disc at a pre-determined frequency.

2.4 Monitoring array

To protect the buildings, highway, and life lines in the zone influenced by the tunnel excavation, monitoring arrays were installed. Fig. 6 showed the section of monitoring array 2A-1. At this location, the tunnel depth was 23.1 m, and the tunnel outside diameter was 6.10 m. Eight shallow settlement indicators (SSI) were arranged on the ground surface to monitor the magnitude and extent of ground deformation due to tunnel excavation.

Fig. 5. Worn cutter-disc after tunneling in cobble and gravelly soil.

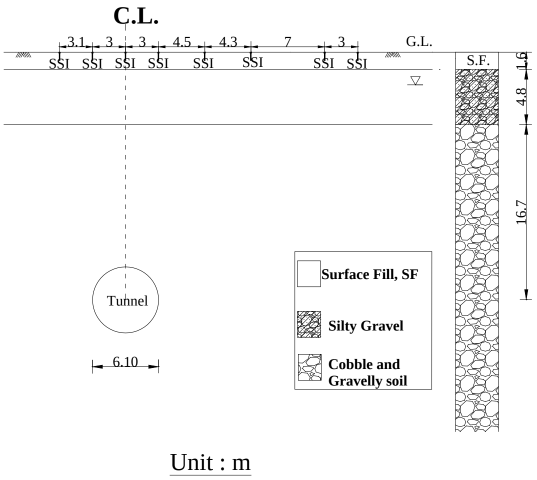

Fig. 6. Section of monitoring array 2A-1.

3 SETTLEMENT-TIME RELATIONSHIP

Fang et al. (1993) proposed that the settlement-time relationship due to shield tunneling in cohesive soils can be described with the hyperbolic model as follows:

$$S(t) = \frac{t}{a + bt} \qquad (1)$$

Where S(t) is the surface settlement as a function time; t is the time after the passage of the face; and a and b are hyperbolic parameters.

Fig. 7 (a) to (d) illustrated the development of surface settlement with time monitored at SSI 6, 17, 28 and 39. It may be observed in these figures that the maximum surface was reached at approximately 30 days after the passage of the face. The maximum surface settlement achieved was only 5 to 6 mm. The field monitored data were in fairly good agreement with the curves estimated with the hyperbolic model.

4 SURFACE SETTLEMENT TROUGHS

In this section, ground settlement troughs due to EPB shield tunneling through gravelly soils were reported. Peck (1969) suggested that the surface settlement trough over a single circular tunnel can usually be approximated by the error function or normal probability curve as follows:

$$S(y) = S_{max} \times \exp\left(\frac{-y^2}{2i^2}\right) \qquad (2)$$

Where S(y) is the settlement at offset distance y from the tunnel center line (tunnel axis), S_{max} is the maximum settlement above tunnel center line, and i is the distance from the inflection point of the trough to the center line. The parameter i is commonly used to represent the width of the settlement trough.

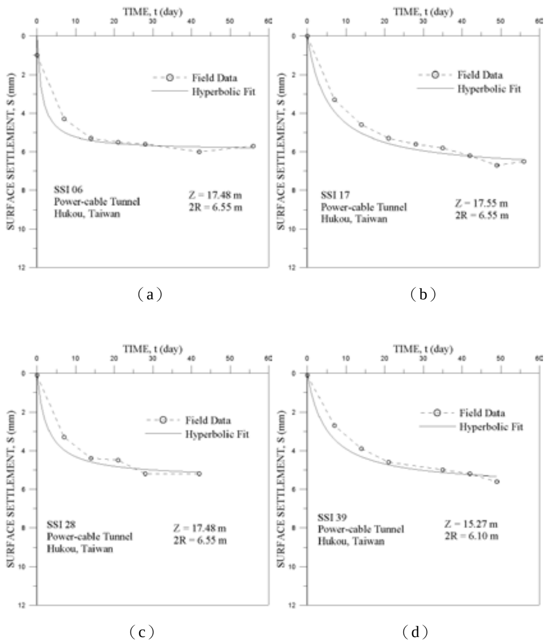

Fig. 7. Monitored settlement-time relationship.

Table 1. Predicted maximum surface settlement in clay and sand.（after Fujita, 1982）

Additional Measures	Type of Soil	Predicted Maximum Surface Settlement and Errors（mm）			
		Open Shield	Blind Shield	Slurry Shield	EPB Shield
Not Adopted	Clay	100 ± 30	40 ± 20	40 ± 10	60 ± 25
	Sand	-	-	-	20 ± 10
Adopted	Clay	-	30 ± 20	-	-
	Sand	40 ± 30	-	-	-

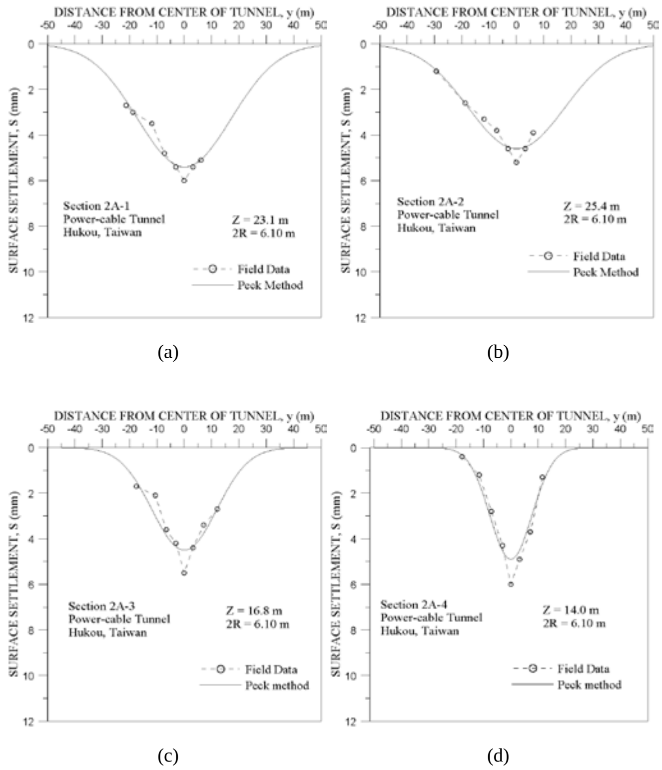

Fig. 8. Field monitored surface settlement troughs.

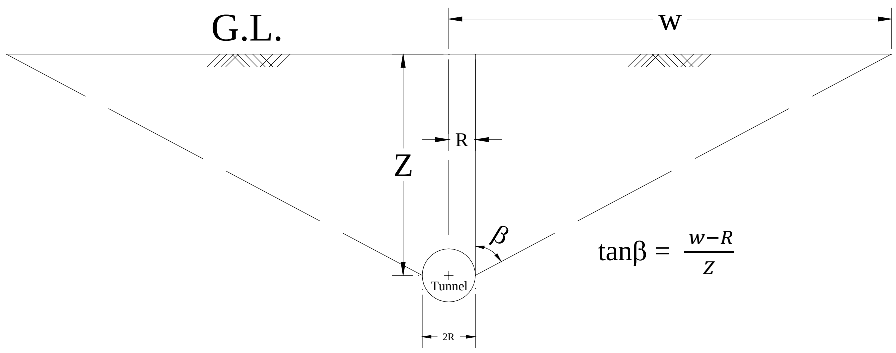

Fig. 9. Settlement trough width and β angle. (after Cording and Hansmire, 1975)

4.1 Maximum surface settlement

The surface settlement troughs measured at sections 2A-1, 2A-2, 2A-3 and 2A-4 were shown in Fig. 8 (a), (b), (c) and (d), respectively. It can be seen in these figures, the field data were in fairly good agreement with the normal distribution curves estimated with Peck's method.

Based on 94 cases in Japan after 1965, Fujita (1982) summarized the maximum surface settlement due to shield tunneling in clay and sand. Table 1 indicated, for tunneling with EPB shields in clay, the maximum surface settlement ranged from 35 to 85 mm. For tunneling with EPB shields in sand, the maximum surface settlement varied from 10 to 30 mm. However, in Fig. 7 and 8, for tunneling with EPB shields in cobble and gravelly soils, the measured maximum surface settlement was only 5 to 6 mm. It may be concluded that, for tunneling with EPB shields, the maximum surface settlements induced in cobble and gravelly soils were significantly less than those induced in clayey and sandy soil deposits. This was most probably due to the high stiffness and shear strength of the gravelly soil, which reduced the ground deformation due to subsurface excavation.

4.2 Width of surface settlement trough

As indicated in Fig. 9, Cording and Hansmire (1975) defined the relationship between the settlement trough width and the β angle as follows:

$$\tan\beta = \frac{w-R}{z} \qquad (3)$$

Cording and Hansmire (1975) reported, for tunnels driven through rock, stiff clay, and sand above ground water table (GWT), the β angle varied from 11^o to about 26^o. For tunnels driven through soft to hard clay, the β angle changed from 26^o to about 50^o.

In Fig. 8(b), for the tunnel with an outside diameter of 6.1 m was constructed at the depth of 25.4 m, the width of the settlement trough was nearly 100 m. For this settlement trough, the β angle was approximately 62^o, which was apparently higher than those induced in stiff clay, sand above GWT, and soft to hard clay. It may be concluded that, for EPB shield tunneling in cobble and gravelly soils, the induced settlement trough could be wider than those induced in stiff clay, sand above GWT, and soft to hard clay. However, more field evidence and investigation is needed for a more solid conclusion.

5 CONCLUSIONS

Based on the EPB shield tunneling through cobble and gravelly soils in Hsinchu, the following conclusions were drawn.

The maximum surface settlement was reached at approximately 30 days after the passage of the face. The maximum surface settlement achieved was only 5 to 6 mm. The field monitored data were in fairly good agreement with the curves estimated with the hyperbolic model.

The maximum surface settlements induced in cobble and gravelly soils were significantly less than those induced in clayey and sandy soils. This was most probably due to the high stiffness and shear strength of the gravelly soil, which reduced the ground deformation due to subsurface excavation.

For EPB shield tunneling in cobble and gravelly soils, the induced settlement trough was wider than those induced in stiff clay, sand above GWT, and soft to hard clay.

ACKNOWLEDGEMENTS

The authors thank Taiwan Power Company, Sinotech Engineering Consultants, Chieh-Hsing Construction Company, and Shimizu Corporation for providing valuable information and support.

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